Partial Environmental Life-Cycle Inventory of Single-family Houses

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ABSTRACT

For the last few decades, the general public has been concerned with the condition of the environment. In response to this trend, research is now being conducted to determine how "environmentally friendly" or "green" building materials are. One method to assess environmental attributes is to perform an environmental life-cycle inventory (LCI). An LCI is an estimate of the materials used, energy used, and the emissions to air, land, and water associated with manufacture of a product, operation of a process, or provision of a service. The methodology for conducting LCIs has been documented by the U.S. EPA, the Society of Environmental Toxicology and Chemistry (SETAC), and the International Organization for Standardization (ISO).

Environmental life-cycle inventories (LCI) were performed for a typical single-family house constructed with various exterior wall assemblies. The house was a 228 square meter (2,450 square foot), two-story residential building with an attached two-car garage. Wall assemblies included traditional wood framing, ICFs (insulating concrete forms), and concrete masonry units (CMU). LCIs were performed over an assumed 100-year life of the house and considered construction, material use and waste, occupant energy use, replacement/repair, and demolition. The houses were modeled in five or ten cities, depending on the exterior wall materials, representing a range of U.S. climates.

The LCI is partial because it does not include the embodied energy or the emissions from the production of non-cement-based building materials, such as wood, steel, and plastics. It also does not include the upstream profiles of fuel and electricity production and distribution.

The results show that occupant energy use accounts for most of the life-cycle energy use of the ICF, CMU, and the wood-frame houses. Occupant energy use includes heating and cooling, cooking, laundry, and other miscellaneous activities. The house life-cycle energy is primarily a function of climate and occupant behavior—not concrete content. Most of the life-cycle emissions to air are from the combustion of household natural gas for heating and hot water—not from the production of concrete. Results may change when a full LCI is performed.

INTRODUCTION

The Portland Cement Association (PCA) is currently developing environmental life-cycle inventory (LCI) data for use in evaluating environmental aspects of concrete products. An LCI is the compilation and quantification of energy and material inputs and outputs of a product system. The ultimate goal of this endeavor is to use the LCI data to conduct a life-cycle *assessment* (LCA) of concrete products. The LCA will quantify the *impacts* of concrete products on the environment in such categories as climate change, acidification, nutrification, natural resource depletion, and risks to human health. An LCA can be used to compare the environmental impacts of concrete products with competing construction products. The LCI data will also be available for incorporation into existing and future LCA models, which are designed to compare construction material and system alternatives, and to improve construction material production processes. The purpose of this paper is to compare the partial LCIs of houses constructed

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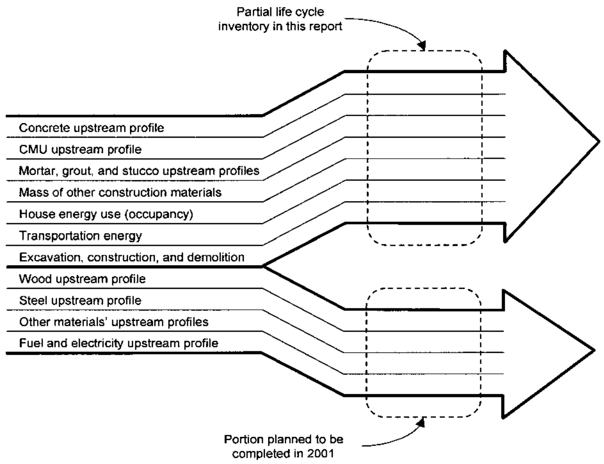

Figure 1 *Material and energy inputs included in the partial LCI.*

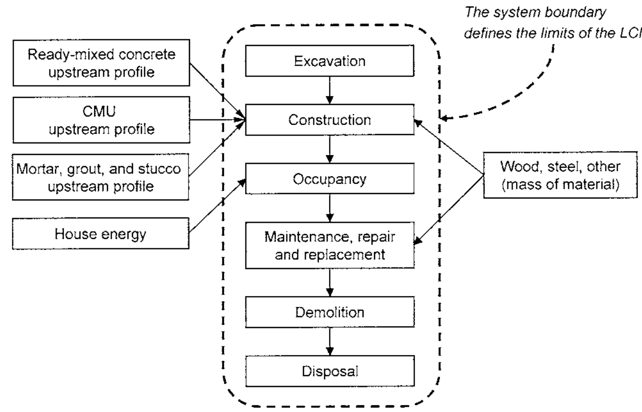

Figure 2 *System boundary for house environmental life-cycle inventory.*

of wood frame, concrete masonry units (CMU), and insulated concrete forms (ICF).

The methodology for conducting an LCI has been documented by the United States Environmental Protection Agency (EPA 1993), the Society of Environmental Toxicology and Chemistry (SETAC 1993), and the International Organization for Standardization (ISO 1997). The partial LCI in this report follows the guidelines proposed by SETAC. These guidelines parallel the standards proposed by ISO in ISO14040, *Environmental Management—Life Cycle Assessment—Principles and Framework*, ISO 14041, *Environmental Management—Life Cycle Assessment—Goal and Scope Definition and Inventory Analysis*, and other ISO and EPA documents.

The house life cycle comprises the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI in this paper includes the upstream profile of ready-mixed concrete, concrete masonry units, mortar, grout, and stucco (Nisbet et al. 2000). The PCA intends to include the upstream profiles of other materials, such as wood and steel, and fuels, such as coal and electricity, once a suitable database is found. Furthermore, water usage from upstream profiles and from household occupants will also be included. Figure 1 shows the material and energy inputs that are included in this partial LCI.

The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation, and it includes the upstream profiles of concrete, CMUs, mortar, grout, and stucco. The masses of other building materials used in the house are included, and they can be used as inputs in existing and future LCA models.

The same floor plan is used for the wood frame, CMU, and ICF houses. The houses are designed to meet the requirements of the 1998 *International Energy Conservation Code* (ICC 1998) because of its wide use as an energy code in the United States. The long-term energy consumption of a building depends on local climate, so the houses are modeled in a variety of climates. House energy consumption is modeled on an hourly basis with building energy simulation software that uses the DOE 2.1E calculation engine (Eley 1999).

SYSTEM BOUNDARY

The house life-cycle system boundary, shown in Figure 2, defines the limit of the partial LCI. It includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The system boundary also includes (1) the upstream profiles of concrete, CMUs, mortar, grout, and stucco; (2) the mass of other building materials used; (3) occupant energy-use; and (4) transportation energy. The transportation energy consists of the energy to transport materials from their place of origin to the building site and from the building site to the landfill and the transportation energy in the upstream profiles.

The system boundary excludes human resources, the infrastructure, accidental spills, and impacts caused by humans.

HOUSE DESCRIPTION

The house described in this paper is based on the designs of typical houses currently being built in the United States. The house is a two-story single-family building with four bedrooms, 2.7-m (9-ft) ceilings, a two-story foyer and family room, and an attached two-car garage. The house has 228 m^2 (2,450 ft^2) of living space, which is somewhat larger than the 1998 U.S. average of 203 m^2 (2,190 ft^2) (U.S. Department of Housing and Urban Development and U.S. Department of

Commerce 1999). The size of the house is based on the average size of ICF houses constructed in the United States (PCA 1999). Figures 3 and 4 present the floor plans.

The wood frame and CMU houses were modeled in five cities, representing a range of U.S. climates: Tucson, Arizona (warm with large temperature swings); Lake Charles, Louisiana (warm with moderate temperature swings); Denver, Colorado (cold with large temperature swings); St. Louis, Missouri (moderate temperature); and Minneapolis, Minnesota (cold with moderate temperature swings). The wood-frame and ICF houses were also modeled in five cities, representing a range of U.S. climates: Phoenix, Arizona (warm with large temperature swings); Miami, Florida (warm with moderate temperature swings); Washington, DC (moderate temperature); Seattle, Washington (moderate temperature); and Chicago (cold with moderate temperature swings). These climates represent a range from hot to cold climates and climates with moderate to high daily temperature swings. The climates where thermal mass works best generally have large daily temperatures swings and temperatures that rise above and below the balance point of the building.

As previously stated, the building envelope in each city is designed to meet the minimum requirements of the 1998 *International Energy Conservation Code* (IECC), using standard building materials (ICC 1998). Variations in regional building materials and practices, such as the use of crawl spaces and basements, are not considered in order to simplify the analyses and in order to compare energy use across all cities.

In all cities, the house is slab-on-grade construction. The slab-on-grade floor consists of carpeted 150-mm (6-in.) thick normal-weight concrete cast on soil. The U-factor of the floor is 1.53 $W/m^2{\cdot}K$ (0.27 $Btu/h{\cdot}ft^2{\cdot}°F$). Although the IECC requires perimeter insulation for slabs-on-grade in most areas of the United States, commonly used and accepted energy modeling software cannot model perimeter insulation. Therefore, the slab-on-grade is uninsulated.

In all cities except Minneapolis, the exterior walls of the wood-frame house consist of medium-colored aluminum siding, 12-mm (½-in.) plywood, R_{SI}-1.9 (R-11) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. In Minneapolis, the exterior walls of the wood-frame house consist of medium-colored aluminum siding, 12-mm (½-in.) plywood, R_{SI}-2.3 (R-13) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board.

The exterior walls of the CMU house in Lake Charles and Tucson consist of 16-mm (5/8-in.) light-colored portland cement stucco, 200-mm (8-in.) CMU with partly grouted insulated cells,[1] wood furring, and 12-mm (½-in.) painted gypsum board. The exterior walls of the CMU house in St. Louis and Denver consist of 16-mm (5/8-in.) light-colored portland cement stucco, 200-mm (8-in.) CMU with partly grouted uninsulated cells, wood furring with R_{SI}-1.9 (R-11) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. In Minneapolis, the exterior walls of the CMU house consist of 16-mm (5/8-in.) light-colored portland cement stucco, 200-mm (8-in.) CMU with partly grouted uninsulated cells, wood furring with RSI-2.3 (R-13) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. In all cities, the nominal weight of the CMU is assumed to be 1,840 kg/m^3 (115 lb/ft^3) with U-factors as presented in ASHRAE Standard 90.1-1999 (ASHRAE 1999).

The exterior walls of the ICF house consist of medium-colored aluminum siding; flat panel ICF system with 50 mm (2 in.) expanded polystyrene insulation, 150 mm (6 in.) normal weight concrete, and 50 mm (2 in.) expanded polystyrene insulation with plastic ties; and 12-mm (½-in.) painted gypsum board. The ICF construction is a typical flat panel ICF system. For all house styles, all exterior garage walls (except the front wall of the garage, which has overhead doors) and the common wall between house and garage are of the same construction as the exterior walls of the house. The front wall of the garage is modeled as a low-mass light-colored wall with a U-factor of 2.8 $W/m^2{\cdot}K$ (0.50 $Btu/h{\cdot}ft^2{\cdot}°F$). Interior walls are wood-frame construction and uninsulated.

Roofs are wood-frame construction with R_{SI}-3.3, R_{SI}-5.3, or R_{SI}-6.7 (R-19, R-30 or R-38) fiberglass batt insulation, depending on location, as indicated in Tables 1 and 2, and are covered with medium-colored asphalt shingles.

Windows are primarily located on the front and back façades, and the overall window-to-exterior wall ratio is 16%. The windows are chosen to meet the IECC requirements for solar heat gain coefficient (SHGC) and U-factor. They consist of double pane glass with a low-E coating. To meet the SHGC requirement, windows in Lake Charles, Tucson, Miami, and Phoenix are tinted and contain air in the space between panes. Windows in other cities are not tinted and contain argon gas in the space between panes. Interior shades or drapes are assumed to be closed during periods of high solar heat gains. Houses are assumed to be located in new developments without trees or any other form of exterior shading.

Tables 1 and 2 present the assembly U-factors used in the analyses. In most cases, using typical building materials results in assemblies that exceed the IECC U-factor requirements.

The HVAC system consists of a natural gas high-efficiency forced-air system with a high-efficiency central air conditioner. Additional assumptions regarding hot water usage, thermostat setbacks, and occupant energy use are available in published reports (Gajda and VanGeem 2000a, concrete masonry; Gajda and VanGeem 2000b, insulating concrete form).

1. "Partly grouted insulated cells" means that some CMU cells are grouted, while others contain insulation. Likewise, "partly grouted uninsulated cells" means that some CMU cells are grouted, while others are empty (do not contain insulation or grout). Grouted cells typically contain reinforcing steel. *Partly grouted* is assumed to mean cells are grouted 80 cm (32 in.) on center vertically and 120 cm (48 in.) on center horizontally (ASHRAE 1999).

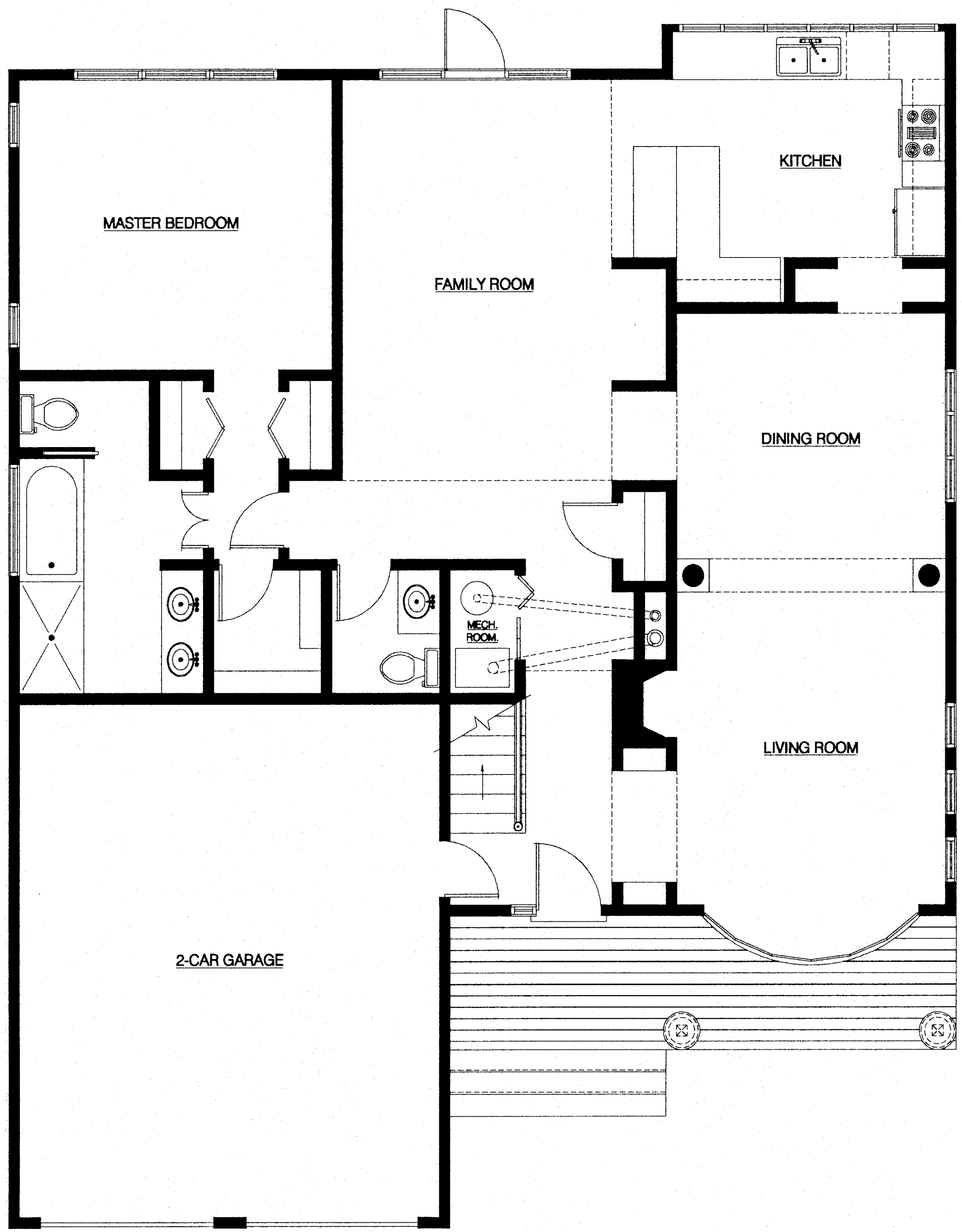

Figure 3 *Floor plan of the lower level.*

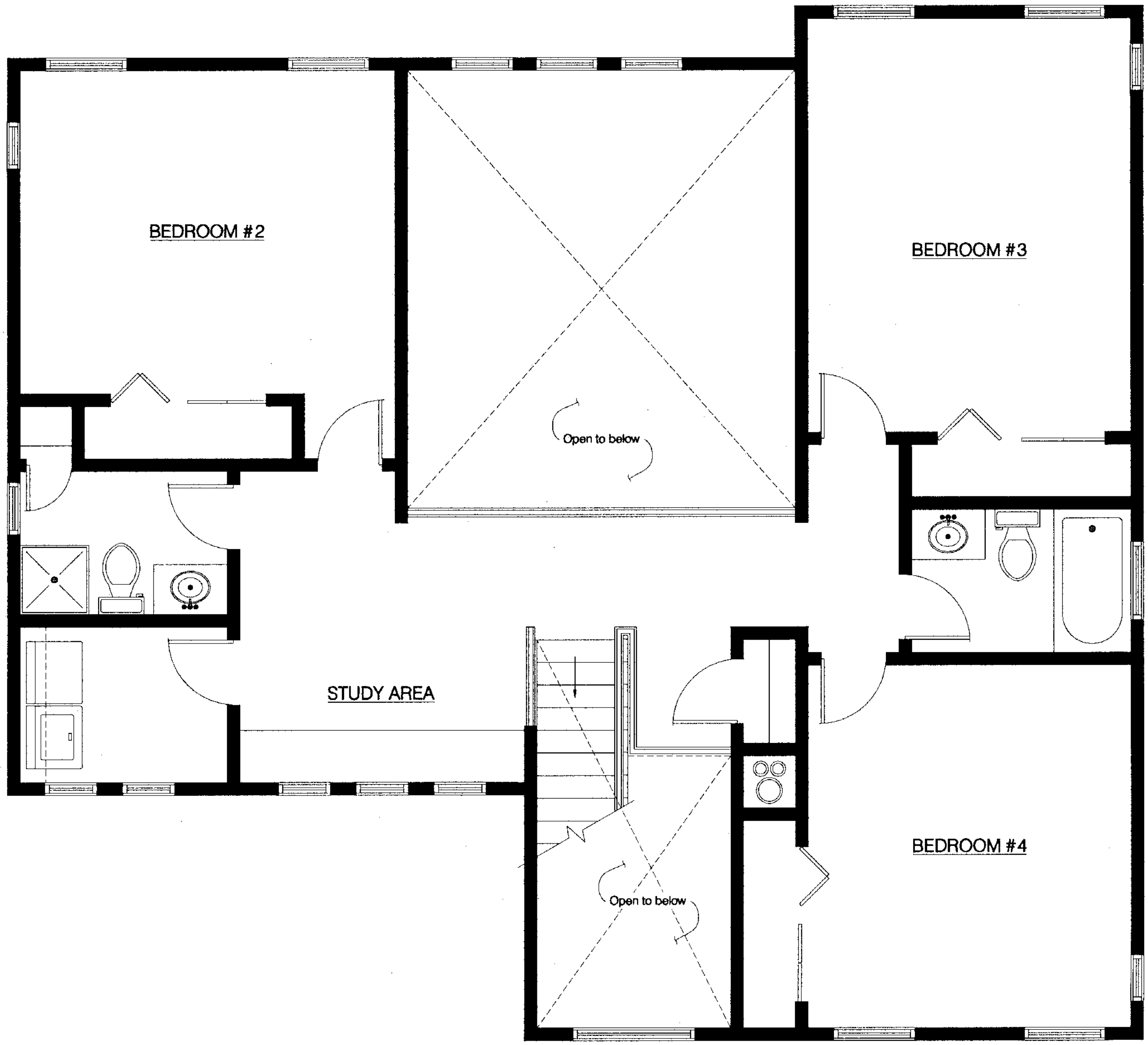

Figure 4 *Floor plan of the upper level.*

TABLE 1
Assembly U-Factors for Cities Used in CMU and Wood-Frame Analyses*

Location	Walls				Roof**		Windows	
	Wood Frame		Mass (CMU)					
	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$
Lake Charles	0.47	0.082	0.85	0.150	0.18	0.032	2.4	0.43
Tucson	0.47	0.082	0.85	0.150	0.18	0.032	2.4	0.43
St. Louis	0.47	0.082	0.44	0.078	0.18	0.032	1.5	0.27
Denver	0.47	0.082	0.44	0.078	0.15	0.026	1.5	0.27
Minneapolis	0.42	0.074	0.41	0.073	0.15	0.026	1.5	0.27

* The maximum U-factor is equal to the inverse of the minimum R-value.
** R_{SI}-5.3 (R-30) attic insulation was used in Lake Charles, Tucson, and St. Louis. R_{SI}-6.7 (R-38) attic insulation was used in Denver and Minneapolis.

TABLE 2
Assembly U-Factors for Cities Used in ICF and Wood-Frame Analyses*

Location	Walls				Roof**		Windows	
	Wood Frame		Mass (CMU)					
	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot °F}$
Miami	0.47	0.082	0.31	0.055	0.27	0.048	2.4	0.43
Phoenix	0.47	0.082	0.31	0.055	0.18	0.032	2.4	0.43
Seattle	0.47	0.082	0.31	0.055	0.18	0.032	1.5	0.27
Washington	0.47	0.082	0.31	0.055	0.18	0.032	1.5	0.27
Chicago	0.47	0.082	0.31	0.055	0.15	0.026	1.5	0.27

* The maximum U-factor is equal to the inverse of the minimum R-value.
** R_{SI}-3.3 (R-19) attic insulation was used in Miami, R_{SI}-6.7 (R-38) attic insulation was used in Chicago, and R_{SI}-5.3 (R-30) attic insulation was used in the remaining cities.

Air infiltration rates are based on ASHRAE Standard 62 (ASHRAE 1989). The air infiltration rate is 0.35 air changes per hour (ACH) in the living areas of the house and 2.5 ACH in the unconditioned attached garage. A family of four is assumed to live in the house.

The life of the house is assumed to be 100 years. The maintenance, repair, and replacement schedules for various building components are based on the authors' professional judgment and are shown in Table 3.

Additional information on each house in each city is presented in published reports (Marceauet et al. 2000a, concrete masonry; Marceau et al. 2000b, insulating concrete form).

INVENTORY ANALYSIS

The SETAC guidelines (SETAC 1993) indicate that inputs to a process do not need to be included in an LCI if (1) they are less than 1% of the total mass of the processed materials or product, (2) they do not contribute significantly to a toxic emission, or (3) they do not have a significant associated energy consumption.

Material Inputs

The material inputs to construction, maintenance, repair, and replacement are calculated from the house plans and elevations and from the house component replacement schedule. Tables 4 and 5 show a summary of the material inputs over the 100-year life of the house in each city.

All houses contain similar amounts of wood. For example, in all houses, the roof, the interior walls, and the second-story floor are framed with wood. In addition, the CMU house has interior wood furring and wood framing around the doors and windows to allow for placement of insulation. There is more gypsum wallboard in the ICF house because the exposed ICF surfaces in the garage are sheathed with gypsum wallboard for reasons of fire safety. In the wood-frame house, the common wall between the garage and house is required to be sheathed with gypsum wallboard, but the rest of the garage is

TABLE 3
House Component Replacement Schedules

House component	Replacement schedule (years)
Siding, air barrier, and exterior fixtures	33.3
Stucco	50
Latex and silicone caulking	10
Paint, exterior	5
Doors and windows	33.3
Roofing*	20 and 40
Gable and ridge vents	33.3
Bathroom fixtures	25
Bathroom tiles and backer board	25
Paint, interior	10
Carpet and pad	10
Resilient flooring, vinyl sheet	10
Bathroom furniture (toilet, sink, etc.)	25
Garbage disposal	20
Furnace	20
Air conditioner	20
Interior and exterior luminaries	33.3
Water heater	20
Large appliances	15
Manufactured fireplace	50
Kitchen and bathroom casework	25
Kitchen counter tops	25

* A new layer of shingles is added every 20 years, and every 40 years the existing layers of felt and shingles are replaced with a new layer of felt and shingles.

not. In the CMU house, the CMU provides adequate fire safety and none of the garage wall surfaces is required to be sheathed. The material inputs also include packaging. Construction waste is included in the mass of materials listed in Tables 4 and 5.

The concrete material upstream profile is based on the upstream profile for 20 MPa (3,000 psi) concrete, CMU concrete, mortar, grout, and stucco. The mix proportions are presented in Table 6. Concrete mix proportions vary depending on available materials and suppliers. The houses in the cooler climates also have more cement-based materials because they have deeper concrete foundations. Detailed quantities of cementitious materials in each house in each city are presented in published reports (Marceau et al. 2000a, concrete masonry; Marceau et al. 2000b, insulating concrete form).

Energy Inputs

The energy inputs to the partial LCI are made up of the energy inputs to excavation, construction, maintenance, occupancy, demolition, and disposal. The partial LCI also includes energy used to produce ready-mixed concrete and CMUs. This is the embodied energy of concrete and it is part of the concrete upstream profile.

Excavation and Construction

Most of the energy used in excavation and construction is for transporting materials from their place of origin to the house construction site. Site energy used by excavation and construction equipment is assumed to be less than 1% of the life-cycle energy, so it is not included in the LCI. Most of the energy used in maintenance, repair, and replacement is used to transport materials from their place of origin to the house. This transportation energy is included in the transportation values in Tables 7 and 8. Detailed information on transportation energy is available in the published reports (Marceau et al. 2000a, concrete masonry; Marceau et al. 2000b, insulating concrete form).

Concrete Embodied Energy

Tables 7 and 8 also show the embodied energy of concrete and other cement-based products in each house in each city. The embodied energy includes energy from the transportation of primary materials from their source to the cement plant, the ready-mixed concrete plant, and the CMU plant. It also includes the energy and emissions from operations at cement, ready-mixed concrete, and CMU plants. It does not include upstream profiles of fuels or electricity. The embodied energy of the cement-based materials in the house is directly related to the amount of cement-based materials used in the house. Although cement makes up less than 10% by weight of ready-mixed concrete, about 70% of the energy embodied in concrete is consumed in the cement manufacturing process (Nisbet et al. 2000).

Household Occupant Energy Use

Energy simulation software is used to model the annual house energy consumption (Eley 1999). This software uses the United States Department of Energy DOE 2.1-E hourly simulation tool as the calculation engine. It is used to simulate hourly energy use and peak demand over a typical one-year period. Because heating and cooling loads vary with solar orientation, each house is modeled four times—once for the front of the house facing each of the four cardinal points (north, south, east, and west). Then the total energy consumption for heating, cooling, hot water, and occupant use is averaged to produce a building-orientation independent energy consumption. Results for the 100-year life are presented in Tables 7 and 8.

The data presented in Table 7 show that the CMU house has occupant energy use similar to that of the wood-frame

TABLE 4a
House Materials List for Cities Used in CMU and Wood-Frame Analyses (SI Units)*

	Wood-frame house					Normal weight CMU house				
Material, kg	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minneapolis**	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minneapolis**
Ready-mixed concrete**	70,700	76,200	92,700	109,200	136,700	70,700	76,200	92,700	109,200	136,700
CMUs, normal weight	0	0	0	0	0	63,500	63,500	63,500	63,500	63,500
Fiber-cement backer board	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Mortar	0	0	0	0	0	35,900	35,900	35,900	35,900	35,900
Grout	0	0	0	0	0	3,900	3,900	3,900	3,900	3,900
Stucco	0	0	0	0	0	23,800	23,800	23,800	23,800	23,800
Metal**	3,500	3,500	3,700	3,900	4,300	4,200	4,300	4,500	4,700	5,100
Wood	20,400	20,400	20,400	20,400	20,400	19,500	19,500	19,500	19,500	19,500
Gypsum wallboard	8,900	8,900	8,900	8,900	8,900	8,000	8,000	8,000	8,000	8,000
Insulation, polystyrene**	0	30	120	210	360	120	150	120	210	360
Insulation, fiberglass	540	540	540	630	630	330	330	540	630	630
Polymers, various	10,200	10,200	10,200	10,200	10,200	10,100	10,100	10,100	10,100	10,100
Roofing materials	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800
Windows	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100
Tile	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
Lighting products	600	600	600	600	600	600	600	600	600	600
Electrical wire	110	110	110	110	110	110	110	110	110	110
Shipping weight, various	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500
Total materials, kg	**134,500**	**140,100**	**156,900**	**173,800**	**201,900**	**248,400**	**254,000**	**270,900**	**287,800**	**315,900**

* Includes items replaced during the 100-year life.
** More material is used in colder climates because foundations are deeper.

TABLE 4b
House Materials for Cities Used in CMU and Wood-Frame Analyses (IP Units)*

Material, lb	Wood-frame house					Normal weight CMU house				
	Lake Charles	Tucson	St. Louis	Denver	Minneapolis	Lake Charles	Tucson	St. Louis	Denver	Minneapolis
Ready-mixed concrete**	155,800	167,900	204,300	240,700	301,400	155,800	167,900	204,300	240,700	301,400
CMUs, normal weight	0	0	0	0	0	140,000	140,000	140,000	140,000	140,000
Fiber-cement backer board	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400
Mortar	0	0	0	0	0	79,100	79,100	79,100	79,100	79,100
Grout	0	0	0	0	0	8,700	8,700	8,700	8,700	8,700
Stucco	0	0	0	0	0	52,400	52,400	52,400	52,400	52,400
Metal**	7,600	7,800	8,200	8,700	9,500	9,400	9,500	10,000	10,500	11,200
Wood	45,000	45,000	45,000	45,000	45,000	42,900	42,900	42,900	42,900	42,900
Gypsum wallboard	19,600	19,600	19,600	19,600	19,600	17,700	17,700	17,700	17,700	17,700
Insulation, polystyrene**	0	70	260	460	790	260	330	260	460	790
Insulation, fiberglass	1,200	1,200	1,200	1,380	1,380	720	720	1,200	1,380	1,380
Polymers, various	22,600	22,600	22,600	22,600	22,600	22,200	22,200	22,200	22,200	22,200
Roofing materials	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800
Windows	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900
Tile	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Lighting products	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300
Electrical wire	250	250	250	250	250	250	250	250	250	250
Shipping weight, various	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100
Total materials, kg	**296,500**	**308,900**	**345,900**	**383,200**	**445,000**	**547,700**	**560,000**	**597,300**	**634,600**	**696,400**

* Includes items replaced during the 100-year life.
** More material is used in colder climates because foundations are deeper.

TABLE 5a

House Materials List for Cities Used in ICF and Wood-Frame Analyses (SI Units)*

	Wood-frame house					ICF house				
Material, kg	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete**	70,700	76,200	76,200	87,200	109,200	193,700	199,200	199,200	210,200	232,300
Fiber-cement backer board	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Metal**	3,500	3,500	3,500	3,700	3,900	5,000	5,100	5,100	5,200	5,500
Wood	20,400	20,400	20,400	20,400	20,400	17,200	17,200	17,200	17,200	17,200
Gypsum wallboard	8,900	8,900	8,900	8,900	8,900	9,700	9,700	9,700	9,700	9,700
Insulation, polystyrene**	0	30	30	90	210	1,920	1,950	1,950	2,010	2,130
Insulation, fiberglass	430	540	540	540	630	210	330	330	330	410
Polymers, various	10,200	10,200	10,200	10,200	10,200	10,100	10,100	10,100	10,100	10,100
Roofing materials	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800
Windows	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100
Tile	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
Lighting products	600	600	600	600	600	600	600	600	600	600
Electrical wire	110	110	110	110	110	110	110	110	110	110
Shipping weight, various	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500
Total materials, kg	**134,400**	**140,100**	**140,100**	**151,300**	**173,800**	**258,100**	**263,800**	**263,800**	**275,000**	**297,600**

* Includes items replaced during the 100-year life.
** More material is used in colder climates because foundations are deeper.

TABLE 5b

House Materials List for Cities Used in ICF and Wood-Frame Analyses (IP Units)*

	Wood-frame house					ICF house				
Material, lb	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Ready-mixed concrete**	155,800	167,900	167,900	192,200	240,700	427,100	439,200	439,200	463,500	512,100
Fiber-cement backer board	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400
Metal**	7,600	7,800	7,800	8,100	8,700	11,100	11,200	11,200	11,500	12,200
Wood	45,000	45,000	45,000	45,000	45,000	37,900	37,900	37,900	37,900	37,900
Gypsum wallboard	19,600	19,600	19,600	19,600	19,600	21,300	21,300	21,300	21,300	21,300
Insulation, polystyrene**	0	70	70	200	460	4,240	4,300	4,300	4,440	4,700
Insulation, fiberglass	950	1,200	1,200	1,200	1,380	470	720	720	720	900
Polymers, various	22,600	22,600	22,600	22,600	22,600	22,200	22,200	22,200	22,200	22,200
Roofing materials	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800
Windows	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900
Tile	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Lighting products	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300
Electrical wire	250	250	250	250	250	250	250	250	250	250
Shipping weight, various	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100
Total materials, lb	**296,300**	**308,900**	**308,900**	**333,600**	**383,200**	**569,000**	**581,700**	**581,700**	**606,400**	**656,000**

* Includes items replaced during the 100-year life.
** More material is used in colder climates because foundations are deeper.

TABLE 6a
Mix Design for 20 MPa Ready-Mixed Concrete, CMU Concrete, Mortar, Grout, and Stucco (SI Units)*

	Ready-mixed concrete 20 MPa	CMU concrete	Mortar	Grout	Stucco
Raw material	**kg/m^3 concrete**	**kg/m^3 concrete**	**kg/m^3 mortar**	**kg/m^3 grout**	**kg/m^3 stucco**
Cement	223	208	352	416	352
Water	141	142	208	224	208
Coarse aggregate	1,127	not applicable	not applicable	not applicable	not applicable
Fine aggregate	831	2,033	1,362	1,314	1,362
Lime	not applicable	not applicable	80	48	80
Total	**2,321**	**2,383**	**2,002**	**2,002**	**2,002**

* Concrete mix designs vary. These have been chosen because they are representative of residential concrete.

TABLE 6b
Mix Design for 3,000 psi Ready-Mixed Concrete, CMU Concrete, Mortar, Grout, and Stucco (IP Units)*

	Ready-mixed concrete 3,000 psi	CMU concrete	Mortar	Grout	Stucco
Raw material	**lb/yd^3 concrete**	**lb/yd^3 concrete**	**lb/yd^3 mortar**	**lb/yd^3 grout**	**lb/yd^3 stucco**
Cement	376	350	594	702	594
Water	237	240	351	378	351
Coarse aggregate	1,900	not applicable	not applicable	not applicable	not applicable
Fine aggregate	1,400	3,427	2,295	2,214	2,295
Lime	not applicable	not applicable	135	81	135
Total	**3,913**	**4,017**	**3,375**	**3,375**	**3,375**

* Concrete mix designs vary. These have been chosen because they are representative of residential concrete.

TABLE 7a
Energy Summary for 100-Year Life Cycle in Cities Used for CMU and Wood-Frame Analyses (SI Units)*

	Wood-frame house					CMU house				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minneapolis**	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minneapolis**
Energy, GJ										
Transportation to house	10	11	12	13	15	19	19	21	22	24
Embodied in concrete	52	56	68	80	100	52	56	68	80	100
Embodied in CMUs	0	0	0	0	0	45	45	45	45	45
Embodied in mortar	0	0	0	0	0	16	16	16	16	16
Embodied in grout	0	0	0	0	0	2	2	2	2	2
Embodied in stucco	0	0	0	0	0	11	11	11	11	11
Occupant use	14,430	14,360	22,410	22,850	28,190	14,650	14,490	21,830	21,710	27,530
Transportation to landfill	10	11	12	13	15	19	19	21	22	24
Total	**14,502**	**14,438**	**22,502**	**22,956**	**28,320**	**14,814**	**14,658**	**22,013**	**21,908**	**27,751**
Percent of total energy use,%										
Transportation to house	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Embodied in concrete	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.4
Embodied in CMUs	0	0	0	0	0	0.3	0.3	0.2	0.2	0.2
Embodied in mortar	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1
Embodied in grout	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
Embodied in stucco	0	0	0	0	0	0.1	0.1	0.0	0.0	0.0
Occupant use	99.5	99.5	99.6	99.5	99.5	98.9	98.9	99.2	99.1	99.2
Transportation to landfill	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

* Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.

TABLE 7b
Energy Summary for 100-Year Life Cycle in Cities Used for CMU and Wood-Frame Analyses (IP Units)*

	Wood-frame house					CMU house				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minneapolis**	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minneapolis**
Energy, GJ										
Transportation to house	10	10	11	12	14	18	18	19	21	23
Embodied in concrete	49	53	65	76	95	49	53	65	76	95
Embodied in CMUs	0	0	0	0	0	42	42	42	42	42
Embodied in mortar	0	0	0	0	0	36	36	36	36	36
Embodied in grout	0	0	0	0	0	5	5	5	5	5
Embodied in stucco	0	0	0	0	0	24	24	24	24	24
Occupant use	13,677	13,611	21,241	21,658	26,719	13,886	13,734	20,691	20,577	26,093
Transportation to landfill	10	10	11	12	14	18	18	19	21	23
Total	13,746	13,684	21,328	21,759	26,843	14,077	13,930	20,901	20,801	26,340
Percent of total energy use,%										
Transportation to house	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Embodied in concrete	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.4
Embodied in CMUs	0	0	0	0	0	0.3	0.3	0.2	0.2	0.2
Embodied in mortar	0	0	0	0	0	0.3	0.3	0.2	0.2	0.1
Embodied in grout	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
Embodied in stucco	0	0	0	0	0	0.2	0.2	0.1	0.1	0.1
Occupant use	99.5	99.5	99.6	99.5	99.5	98.6	98.6	99.0	98.9	99.1
Transportation to landfill	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

* Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.

TABLE 8a
Energy Summary for 100-Year Life Cycle in Cities Used for ICF and Wood-Frame Analyses (SI Units)*

	Wood-frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Energy, GJ										
Transportation to house	10	11	11	11	13	20	20	20	21	23
Embodied in concrete	52	56	56	64	80	142	146	146	154	171
Occupant use	10,640	14,510	22,000	21,370	25,600	10,070	13,380	20,030	19,710	23,530
Transportation to landfill	10	11	11	11	13	20	20	20	21	23
Total	**10,712**	**14,588**	**22,078**	**21,456**	**25,706**	**10,252**	**13,566**	**20,216**	**19,906**	**23,746**
Percent of total energy use,%										
Transportation to house	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Embodied in concrete	0.5	0.4	0.3	0.3	0.3	1.4	1.1	0.7	0.8	0.7
Occupant use	99.3	99.5	99.6	99.6	99.6	98.2	98.6	99.1	99.0	99.1
Transportation to landfill	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1

* Does not include upstream profile of electricity, fuel, or materials other than concrete.

TABLE 8b
Energy Summary for 100-Year Life Cycle in Cities Used for ICF and Wood-Frame Analyses (IP Units)*

	Wood-frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Energy, MBtu										
Transportation to house	10	10	10	11	12	19	19	19	20	21
Embodied in concrete	49	53	53	61	76	135	139	139	146	162
Occupant use	10,085	13,753	20,852	20,255	24,264	9,545	12,682	18,985	18,681	22,302
Transportation to landfill	10	10	10	11	12	19	19	19	20	21
Total	**10,154**	**13,826**	**20,925**	**20,338**	**24,365**	**9,716**	**12,858**	**19,161**	**18,867**	**22,506**
Percent of total energy use,%										
Transportation to house	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Embodied in concrete	0.5	0.4	0.3	0.3	0.3	1.4	1.1	0.7	0.8	0.7
Occupant use	99.3	99.5	99.7	99.6	99.6	98.2	98.6	99.1	99.0	99.1
Transportation to landfill	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1

* Does not include upstream profile of electricity, fuel, or materials other than concrete.

TABLE 9a
Summary of 100-Year Life-Cycle Emissions in Cities for CMU and Wood-Frame Analyses (SI Units)*

	Wood-frame house					CMU house				
	Lake Charles	Tucson	St. Louis	Denver	Minneapolis	Lake Charles	Tucson	St. Louis	Denver	Minneapolis
Emission, kg										
Particulate matter	64	64	101	113	143	130	129	165	175	206
CO_2	471,000	431,000	902,000	960,000	1,234,000	502,000	453,000	897,000	929,000	1,223,000
SO_2	34	36	46	54	67	106	108	117	125	138
NO_x	404	375	751	803	1,029	493	457	812	844	1,085
VOC	25	23	45	48	62	30	27	48	50	64
CO	172	159	318	340	435	196	180	330	343	444
CH_4	10	9	18	19	25	11	11	19	20	26

* Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.

TABLE 9b
Summary of 100-Year Life-Cycle Emissions in Cities for CMU and Wood-Frame Analyses (IP Units)*

	Wood-frame house					CMU house				
	Lake Charles	Tucson	St. Louis	Denver	Minneapolis	Lake Charles	Tucson	St. Louis	Denver	Minneapolis
Emission, lb										
Particulate matter	141	141	224	249	315	286	285	364	386	455
CO_2	1,040,000	953,000	1,991,000	2,119,000	2,722,000	1,109,000	1,000,000	1,980,000	2,051,000	2,698,000
SO_2	76	80	102	118	148	233	238	259	275	305
NO_x	892	829	1,657	1,773	2,271	1,088	1,009	1,791	1,862	2,395
VOC	54	51	99	106	136	65	61	107	111	142
CO	379	352	703	750	959	432	398	729	757	981
CH_4	22	20	40	43	55	25	23	42	44	57

* Does not include upstream profile of electricity, fuels, or materials other than cement-based products.

house.This is primarily because both the CMU house and the wood-frame house were modeled with standard materials needed to meet IECC requirements. The ICF house has lower occupant energy use than the wood-frame house in all climates, as shown in Table 8. In the simulations, the ICF house was modeled with a standard ICF wall configuration while the wood-frame house was modeled with standard materials needed to meet IECC requirements. In all cases but one (the wood-frame house in Chicago), the R-values of ICF and wood-frame walls significantly exceed IECC requirements. In general, wood-frame walls have R-values that range from approximately 0% to 100% in excess of IECC requirements, CMU walls have R-values that range from approximately 0% to 50% in excess IECC requirements, and ICF walls have R-values that range from approximately 50% to 200% in excess IECC requirements.

Results also show the thermal mass of the CMU and ICF houses moderates temperature swings and peak loads and results in lower HVAC system capacity requirements.

Demolition And Disposal

Most of the energy used in demolition and disposal is used to transport materials from the house to the landfill. All material is assumed to be transported by tractor trailers using diesel fuel and traveling on paved roads. Disposal energy is listed as transportation to landfill in Tables 7 and 8.

Total Energy Inputs

Tables 7 and 8 show that most of the embodied energy is occupant energy use for this partial LCI. This means that the house life-cycle energy is not sensitive to variations in cement manufacturing, ready-mixed concrete production, CMU production, nor transportation. The house life-cycle energy is

TABLE 10a
Summary of 100-Year Life-Cycle Emissions in Cities for ICF and Wood-Frame Analyses (SI Units)*

	Wood-frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Emission, kg										
Particulate matter	48	59	96	97	121	106	116	149	151	174
CO_2	216,000	360,000	942,000	870,000	1,096,000	222,000	344,000	860,000	810,000	1,014,000
SO_2	33	36	39	43	54	87	90	92	97	108
NO_x	204	320	775	724	910	260	358	762	728	897
VOC	13	20	46	43	54	17	23	46	44	54
CO	87	136	330	307	385	104	146	318	303	373
CH_4	5	8	19	18	22	6	8	18	17	21

* Does not include upstream profile of electricity, fuel, or materials other than concrete.

TABLE 10b
Summary of 100-Year Life-Cycle Emissions in Cities for ICF and Wood-Frame Analyses (IP Units)*

	Wood-frame house					ICF house				
	Miami	**Phoenix**	**Seattle**	**DC**	**Chicago**	**Miami**	**Phoenix**	**Seattle**	**DC**	**Chicago**
Emission, lb										
Particulate matter	105	131	212	214	268	233	256	328	332	383
CO_2	477,000	795,000	2,079,000	1,921,000	2,419,000	489,000	758,000	1,897,000	1,788,000	2,237,000
SO_2	73	80	86	96	120	191	198	204	214	237
NO_x	451	705	1,711	1,598	2,008	573	790	1,682	1,606	1,978
VOC	29	44	102	96	120	37	50	102	98	120
CO	192	299	727	678	850	230	321	701	668	824
CH_4	11	17	42	39	49	13	18	40	38	47

* Does not include upstream profile of electricity, fuel, or materials other than concrete.

primarily a function of climate and occupant behavior. Furthermore, although the CMU house initially contains more embodied energy than the wood-frame house. After seven years in Denver, for example, the cumulative energy use of the wood-frame house exceeds that of the CMU house. After five years in Chicago, the cumulative energy use of the wood-frame house exceeds that of the ICF house.

Material Outputs

The life-cycle material outputs from the house are made up of the material outputs from excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. These can include emissions to air, waste water, and solid waste. Emissions to air are summarized in this paper. More detailed information on emissions to air and other wastes are presented in Marceau et al. (2000a) and Marceau et al. (2000b).

The partial LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency (1999). These emissions consist of particulate matter from point and fugitive sources and the following combustion gases: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). Hazardous air pollutants, such as hydrogen chloride, mercury, dioxins, and furans, are excluded from the house LCI because there is insufficient information to accurately quantify their emissions.

Most of the life-cycle emissions to air are from the two natural gas-burning appliances (furnace and water heater). Tables 9 and 10 show the total life-cycle emissions of each house. These emissions include the emissions from (1) the manufacture of cement, (2) the production of concrete, CMUs, mortar, grout, and stucco, (3) the operation of two natural gas-burning appliances (furnace and water heater), and (4) the transportation of materials to and from the house.

For this partial LCI, the cement-based components of the CMU and ICF houses represent approximately 70% of the total particulate matter released to the air. The cement-based components of a wood-frame house represent approximately 50% of the total particulate matter released to the air. These will be less significant when the electricity generation is included in the LCI.

The production of the cement-based components of the CMU house account for 1% to 4% of the total CO_2 emissions throughout the life of the house. Values for the ICF and wood-frame house are 2% to 9% and 1% to 3%, respectively, of the total CO_2 emissions throughout the life of the house. The production of the cement-based components of the CMU and ICF houses accounts for approximately 90% of the total SO_2 emissions. The production of the cement-based components of the wood-frame house accounts for approximately 85% of the total SO_2 emissions.

Approximately 95% of the CO_2 emissions are from the combustion of natural gas appliances in the CMU and ICF houses. Approximately 98% of the CO_2 emissions are from the combustion of natural gas appliances in the wood-frame house. Approximately 80% of the NO_x emissions are from the combustion of natural gas appliances in the CMU house. Approximately 90% of the NO_x emissions are from the combustion of natural gas appliances in the wood-frame house. In all houses, natural gas appliances contribute an average of 75% to 90% of the emissions of VOC, CO, and CH_4. Results may change when a full LCI is performed.

Solid Waste

At the end of the 100-year life, the house materials and components can be reused and recycled. However, there is little information on how much building material is reused and recycled from the demolition of a building (Hobbs and Kay 2000; ZKA&CSC 1993). So, until reliable data are available, all house materials are assumed to be disposed of in a landfill.

Sensitivity

The life-cycle energy of the three houses is not sensitive to variations in the exterior walls, the manufacturing process of cement, or the production of cement-based materials. Most of the house life-cycle energy is occupant energy use; that is, energy for heating, cooling, lighting, washing, and other uses. After climate, occupant behavior is the single most important factor contributing to energy consumption in a home (Zmeureanu and Marceau 1999).

SUMMARY AND CONCLUSIONS

A partial LCI of three identical houses with wood-frame, CMU, and ICF walls has been carried out according to SETAC guidelines and ISO standards 14040 and 14041. The houses were modeled in five or ten cities, depending on the exterior wall type, representing a range of U.S. climates.

The house is a two-story single-family building with a contemporary design. The house system boundary includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation over a 100-year life. It also includes the upstream profiles of concrete, CMUs, mortar, grout, and stucco and the masses of other building materials used in the house. This partial LCI does not include the emissions from the manufacturer of other building materials such as wood, steel, and plastics. It also does not include the upstream profile of fuel and electricity production and distribution. Results may change when a full LCI is performed.

The results show that occupant energy use accounts for most of the life-cycle energy use of the CMU, ICF, and wood-frame houses. A small portion of the life-cycle energy is due to manufacturing cement and producing concrete, CMUs, mortar, grout, and stucco. The house life-cycle energy is primarily a function of climate and occupant behavior. Furthermore, although the CMU house contains more embodied energy than the wood-frame house, after seven years in Denver, for example, the cumulative energy use of the wood-frame house surpasses that of the CMU house. After five years in Chicago, the cumulative energy use of the wood-frame house surpasses that of the ICF house.

The partial LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency. Most of the life-cycle emissions to air are from the two natural gas-burning appliances (furnace and water heater), not from the production of concrete.

In the next phase of the project, upstream profiles will be included for other materials, such as wood and steel, and fuels, such as coal and electricity, in the house LCI. The ultimate goal is to use the LCI data to conduct a life-cycle assessment (LCA) of the wood-frame, CMU, and ICF houses. The LCA will quantify the impacts of concrete products on the environment in such categories as climate change, acidification, nutrification, natural resource depletion, and risks to human health.

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